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ABSTRACT

Stormwater source control regulations are rapidly diffusing in many countries. Most of these are provisions that limit runoff rates at the parcel-scale, although some references indicate some negative side effects, at the catchment-scale, for this form of regulation. In this paper, we compare, at that scale, the effects of several runoff rate and runoff volume provisions, using a hydrological model calibrated on a real catchment in the Paris region. We considered two main objectives: to avoid sewer overflows and to preserve receiving waters. The results show that runoff volume provisions are more effective in terms of receiving waters preservation than the runoff rate ones. In terms of sewer overflows, both can reach the same performances.

KEYWORDS

Catchment scale; regulation; runoff volume; sewer overflows; source control; urban drainage

INTRODUCTION

In the last four decades, stormwater Source Control (SC), has gained relevance in many countries, mainly for its potential to mitigate negative impacts of fast urbanization and imperviousness increase. Many local authorities in several countries (e.g. France, USA, UK), formulate policies to generalize SC implementation. Yet, choosing a locally "good" policy, able to solve the specific problems of the catchment, is a hard task.

Authorities use several policy instruments from two main groups: voluntary instruments, including both financial and technical support, and compulsory instruments like runoff regulation or taxation (Parikh, 2005; Morison and Brown, 2011). The first instruments' group is likely to produce a more punctual development of SC, in comparison with the second group that can have a more generalized effect. In this paper we are interested on the global hydrological effects of policies, and thus we focus on compulsory instruments.

From the hydrological point of view, regulation or taxation are similar: both require to find a global level of performance and the appropriate technical means to achieve it. Then, the actual mechanism of implementation of these technical means (i.e. a constraint or a tax) does not make a significant difference. Therefore, we can study hydrological effects of regulation only, knowing that, with some adaptations, the results could be applied to a tax instrument.

No theoretical framework is available for the catchment-scale effects of SC, and this makes difficult to find a link between a global objective and a corresponding SC implementation. As a consequence, authorities often based their policies on simplistic approaches, derived from sewer systems' design and focused on runoff peak flow-rate. The outcome is that most of the compulsory instruments in use focus on the runoff rates at the parcel or development scale.

Today, many scientific works converge in criticizing this kind of runoff rates provisions. The first critic is that SC policies explicitly or implicitly aim, in general, to preserve pre-development water balance. This is the case for Low Impact Development (LID) or Water Sensitive Urban Drainage (WSUD) approaches (Morison and Brown, 2011). It has been shown that runoff rate provisions are unable to preserve pre-development water balance. In particular, these provisions do not cope with reduced infiltration volumes and downstream distortion of low-flow regimes (Booth and Jackson, 1997; Fennessey *et al.*, 2001). The second critic is that, also in terms of peak flow-rate, this kind of provision can actually worsen the situation at the catchment-scale (Emerson *et al.*, 2005). Booth and Jackson (1997) proposed, to avoid these problems, to base provisions on runoff characteristics different from runoff rates. Emerson *et al.* (2005), more specifically, suggested to limit runoff volumes..

In this paper we study, through a modelling approach, how the hydrological behaviour of a periurban catchment (480 ha) in the Paris region changes, when SC provisions are applied. In order to evaluate when runoff rate and runoff volume provisions are interchangeable, we compare, for both type of provisions, different levels of constraint.

BACKGROUND

Many researchers (e.g. Emerson *et al.*, 2005) and environmental authorities (*Agences de l'Eau* in France, EPA in the US) argue that SC effects should be analyzed at the catchment-scale, because policy goals are set at that level. Still, while we know the effects of BMPs at the local scale, we do not have a precise insight of what is their global effect at the catchment-scale. As it is impossible to create actual-scale experiments, our knowledge of global effects of SC provisions is mainly based on *ex-post* analysis of actual SC implementations (Petrucci *et al.*, submitted; Meierdiercks *et al.*, 2010). As this kind of studies is, today, too scarce to develop a consistent foundation for SC provisions, policy-makers and researchers have followed two different approaches.

Policy-makers were in the need to develop SC as rapidly as possible to solve urgent concerns (mainly urban floods and receiving waters degradation). Thus, they generally adopted policies with the purpose of promoting the implementation of as many BMPs as possible. The implicit assumption is that if BMPs are effective locally, they will be effective at the catchment-scale. The two general forms of provisions are (i) to set a parcel-scale runoff rate value, valid for all the parcels of the catchment, or (ii) to set a formula to calculate pre-development peak runoff rate for any parcel, to be maintained after development. The first option is generally adopted in France, while the second one is common in the US (Balascio and Lucas, 2009). In the UK, examples of both are in use (Faulkner, 1999).

Researchers tried to compensate the absence of large-scale datasets by attempting modelling approaches, both on real and on "synthetic" catchments, in order to find general rules to guide SC regulation. Konrad and Burges (2001), Fennessey *et al.* (2001), Fang *et al*. (2010), tried approaches based on real catchments, finding that runoff rate provisions are not always effective in reducing catchment-scale runoff for extreme rain events and that, for current rain events, runoff rates can be heavily distorted. In general, water balance at the catchment scale is not preserved. Emerson *et al.* (2005) found that volume-based provisions can be effective in reducing peak flow-rate at the catchment-scale. Goff and Gentry (2006) simulated ponds implementation on a synthetic catchment varying 6 parameters describing both watershed and urban development. They confirmed that, for fully developed watersheds, even if all the parcels maintain pre-development peak runoff rate, it is impossible to maintain it at the catchment-scale, and they suggested to emphasize the use of volume provisions.

The effect of SC on a catchment will depend on both the characteristics of the catchment (topography, geology, climate, urban development) and of the provision (type, level of constraint). Most of the studies cited focus on catchments' variability, while provisions' variability is seldom considered in depth (only Fennessey *et al.* compare five US stormwater ordinances). These studies provide, thus, a growing support to the idea that runoff rate provisions can be ineffective and even harmful for some catchment. However, they do not help defining the specific provisions that can be effective, ineffective or harmful. Similarly, there are evidences that runoff volume provisions can be effective for peak flow-rate reduction at the catchment-scale, but we do not know the link between constraint level and effectiveness.

Because of the dependence on catchment's characteristics, generalization of results obtained on a single catchment should be done carefully. Nevertheless, the analysis of specific case-study can provide information about the possible behaviour (or type of behaviour) that a catchment can have when submitted to SC, and thus orient subsequent research and policy-making efforts. With this purpose we consider, in this paper, a periurban catchment in the Paris region, representative of the regional 1950-2000 urbanization. We test, on the catchment model, a series of runoff rate and runoff volume provisions with different levels of constraint, in order to check how the catchment response to SC is sensitive to provision's characteristics.

EXPERIMENTAL CATCHMENT

In this research, we study an urban catchment in France, 20 km south of Paris, object of several measurement campaigns over the last 10 years. The catchment area is 451 ha - a relevant scale for SC policy-making – and is divided in four municipalities (Figure 1).

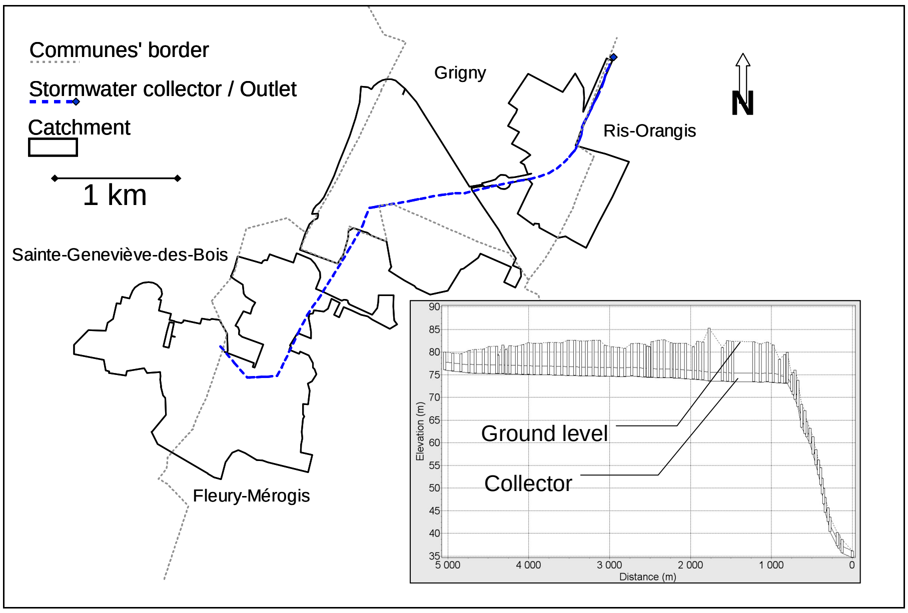

Figure 1. Catchment's and administrative borders. In the box, profile plot of the stormwater collector.

Each municipality is in charge of collecting stormwater, but an inter-municipal authority (Syndicat mixte de la Vallée de l'Orge Aval, SIVOA) is in charge of its transport and treatment. Thus, municipalities own proximity collectors on their territories (not modelled in the current study), drained by a major collector managed by the SIVOA. The latter is also in charge of catchment-wide policies, including SC regulation. After the enforcement, in 2003, of a very strict provision – i.e. all the stormwater has to be infiltrated at the parcel level or, if it is impossible, to be stored and released at very low rates (1 l/s/ha) - SIVOA is currently revising its policy.

Topographically, the catchment is on a *plateau* (see box in figure 1): its upstream two thirds have really small slopes (<0.5%), while the downstream part – on the hillside – is much steeper (5-6%). The catchment was rural until 1960 and drained by small creeks. Since the construction of the main collector from the SIVOA (1968/69), many urban developments took place and were connected to it. The development occurred both as large planning operations (the "Zone opérationnelle d'habitat" – ZOH – is a public housing plan that gives its name to the collector and the catchment) and as gradual urban development. Impervious cover in the catchment is approximately 31%, and urbanization of the area is still in progress. This type of plateau development is typical of the urbanization of the Paris region and of the *villes nouvelles* in the second half of the 20th century.

The stormwater outlet is connected to a group of small sand-pit lakes linked to the Seine river. The outlet is equipped (2003) with a settling unit to protect the lakes from suspended solids and eutrophication.

METHODOLOGY

As the purpose of the study was the assessment of different future scenarios of SC implementation over a catchment, we used a distributed physically-based model. The distribution feature is necessary to take into account the spatial effects due to SC application (Fang et al., 2010), while the physical base allows to describe explicitly the scenarios' characteristics. The chosen model is SWMM 5 (Rossmann, 2004), a widely-used model allowing both traditional and SC drainage simulations (Elliott and Trowsdale, 2007). A useful feature of SWMM is that it can run continuous simulations over long periods (years) with short timesteps (5' in our study). In this way it is possible to evaluate, using the same model, both water-balance indicators (e.g. yearly runoff volumes) and peak flow-rates for extreme events on short time-scales.

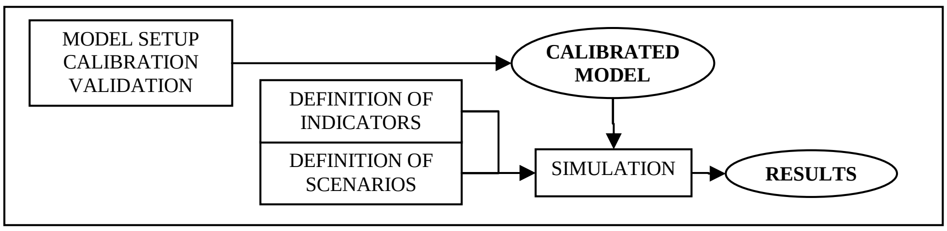

Figure 2. Modelling and simulation procedure.

Model setup, calibration and validation.

First step of the procedure presented in Figure 2, model setup includes the division of the catchment in sub-catchments, the corresponding data-analysis to define each sub-catchment characteristics, the definition of calibration parameters, criteria and algorithm. Calibration and validation phases where performed on data issued from two measurement campaigns operated by the local sanitation authority in 2009 and 2010. Further details of the procedure followed are presented in Petrucci *et al.* (2010).

Performance indicators.
We consider that SC provisions have two main objectives: avoid sewer overflows and preserve receiving waters. The SIVOA fixed, as the reference rain event for BMP dimensioning, a triangular hyetograph with 55 mm of precipitation in 4 hours (return period T=20 years). Thus, to evaluate the first objective, the indicator chosen is the peak flow-rate for this rain event, normalized on the impervious area of the catchment (141 ha). This indicator is noted q_{peak} (l/s/ha).

For the second objective, we consider two indicators: one catchment-specific and one more general:

- In the ZOH catchment, the outfall settling unit has a limited capacity (0.8 m^3/s). It is important, thus, to minimize the annual runoff volume that bypass the treatment. This indicator is noted $V_{0.8}$ (m^3).
- The presence of the treatment unit is catchment-specific: often, stormwater is directly routed to a natural creek or river. In this case, the stability and ecological status of the receiving waters depend on low-flow regimes (Fennessey *et al.*, 2001). A performance indicator for low-flow regimes is the frequency of flow: the fraction of time during which a flow is detected at the outlet. This indicator is noted f_{flow} (-).

These two indicators are computed for a 23-month rainfall series (1/1/2009 to 1/12/2010). The series is not long enough to give statistically relevant results for extreme rain events (T > 1 year), but it is sufficient for current ones (T < 6 months).

Scenarios of SC implementation.
We made 34 simulations: one reference case, corresponding to the calibrated model; 15 peak runoff rate provisions, ranging from q^*=0.5 l/s/ha to q^*=50 l/s/ha; 18 runoff volume provisions, ranging from i^*=0.01 mm to i^*=50 mm. We do not test provisions using pre-development formulas (see *background*) as there is no reference available for the experimental catchment considered.

Runoff rate provisions are modelled through a reservoir for each subcatchment (32 in total), draining runoff from impervious areas. Reservoir and outfalls dimensions are defined through the *rainfalls design method* (Chocat, 1997). Resulting capacities are reported in Table 1. For values of q^*≥15 l/s/ha, the model incurs in numerical instabilities for low flows (~10^{-2} m^3/s). For these cases, thus, computation of f_{flow} is unreliable and will not be presented.

Table 1. Peak runoff rate provisions and corresponding storage volumes.

q^* (l/s/ha)	0.5	1	2	3	5	8	10	15	20	25	30	35	40	45	50
v (m^3/ha)	658	565	485	447	377	323	299	262	252	231	205	184	168	155	145

Runoff volume provisions are modelled as filter strips downstream of each subcatchment. If the subcatchment has an impervious area A_s, the strip stores (as initial losses) a runoff volume of $V=A_s \cdot i^*$. This water is then infiltrated and can be replaced by further runoff. The infiltration model used is Green-Ampt, with parameters corresponding to a silt loam (Rossmann, 2004).

RESULTS AND DISCUSSION

The simulations results, for the three considered indicators, are plotted in Figures 3 to 5. In each figure the x-axes are plotted in the sense of "increasing implementation efforts": moving from left to right the runoff volume to infiltrate increases (lower x-axis) and the maximal runoff rate decreases (upper x-axis). However, as we do not consider "efforts" or costs in the analysis, two vertically aligned points should not be interpreted as having an equivalent cost of implementation.

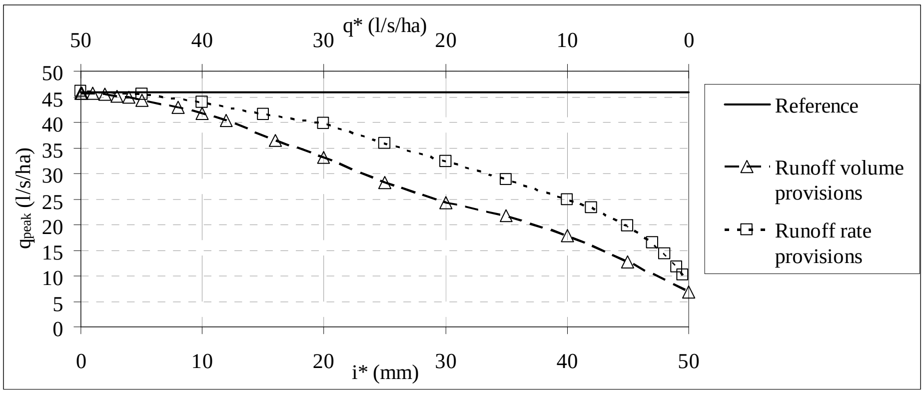

Figure 3. Simulation results for q_{peak}.

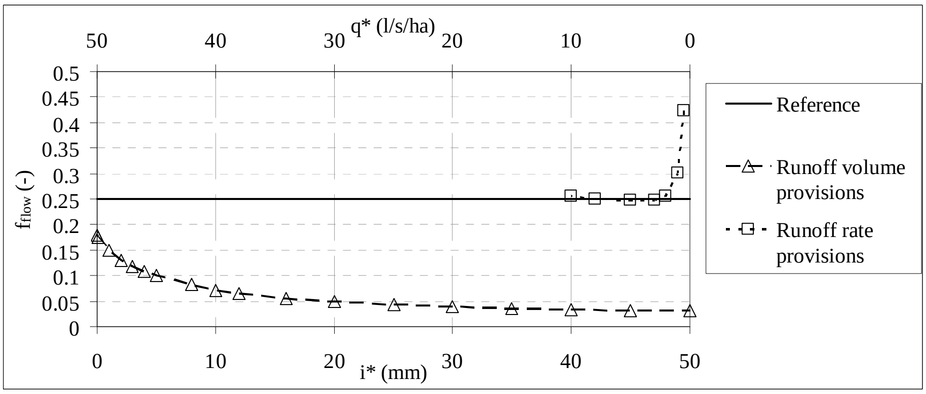

Figure 4. Simulation results for f_{flow}. Results for $q^*\geq 15$ l/s/ha are not shown.

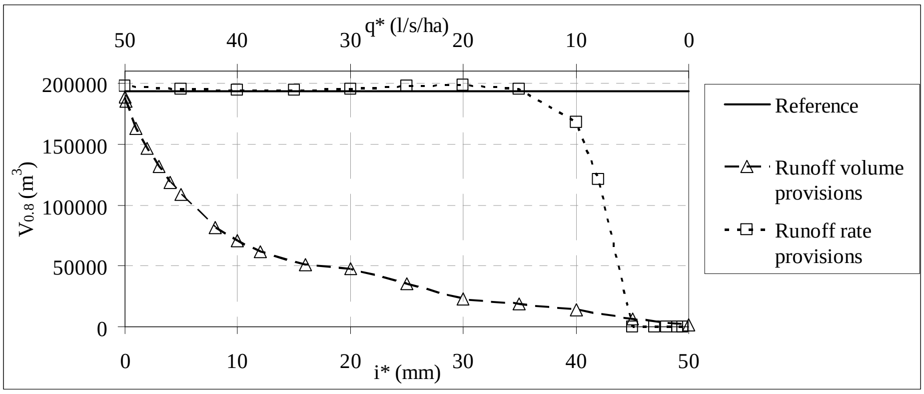

Figure 5. Simulation results for $V_{0.8}$. It represents the water volume bypassing the settling unit.

In Figure 3 is plotted the normalized peak flow-rate for the reference rain event (q_{peak}). For both types of provisions, q_{peak} decreases with efforts. This is positive, as it shows that there are no risks to worsen actual situation for the catchment considered. A second observation is that, for runoff rate provisions, q_{peak} is always greater than q^*. The reason is that, for intense rain events, pervious areas (not controlled by reservoirs) contribute to the peak flow-rate. An important remark is that the range of resulting q_{peak} for both types of provisions is the same (from 50 to 8-10 l/s/ha). Thus, for a given target value of the objective in this range (e.g. 20 l/s/ha), it is always possible to find two corresponding provisions, one runoff rate-based (in the example q^*=5 l/s/ha) and one volume-based (i^*=35 mm).

Figure 4 shows flow frequencies at the catchment outlet (f_{flow}). As it was expected, runoff rate provisions never improve the reference situation, while runoff volume ones always do. More in detail, runoff rate provisions do not affect the indicator for q^*>2 l/s/ha, while for lower values they worsen the situation. With regard to this indicator and this specific catchment, thus, provisions distort low-flow regimes only if they are extremely strict. Runoff volume provisions, on the contrary, rapidly improve the indicator value for i^*<20 mm. This indicator is affected even for extremely small storage values (i^*=0.01 mm): this corresponds to the infiltration effect of filter strips providing no storage (see *Scenarios of SC implementation*).

In Figure 5 is plotted the runoff volume exceeding the treatment unit flow capacity ($V_{0.8}$). Also for this indicator, runoff volume provisions show a continuous improving behaviour, slowing down with increasing constraint values. As in the previous case, a small constraint (e.g. i^*=5 mm) is enough to nearly half the reference value of the indicator. Runoff rate provisions have a more complex behaviour, with 4 different ranges:

- q^* < 5 l/s/ha. Catchment flow-rate is always below 0.8 m^3/s, and thus $V_{0.8}$=0.
- 5 l/s/ha < q^* < 15 l/s/ha. In this range the provisions show a “good” behaviour: increasing efforts improve values of the indicator.
- 15 l/s/ha < q^* < 30 l/s/ha. In this range, the effect of provisions is a worsening of the indicator values. The reason of this fact is that, during reservoir emptying, the catchment flow-rate is above 0.8 m^3/s for longer durations than in the reference case.
- q^* > 30 l/s/ha. No significant variation from the reference case.

Comparing the results for the three indicators, we observe that runoff volume provisions have a simpler behaviour than runoff rate ones. In fact, in the three cases, volume provisions show always a monotonous trend: increasing efforts generate improvements in the indicators value. On the contrary, runoff rate provisions have threshold-effects and, for some ranges, can produce degradation of some indicators value. These thresholds and the existence of critic ranges are catchment specific: for example, for f_{flow}, provisions do not change the indicator value if the emptying time of the reservoirs for a rain event is shorter than the duration of the corresponding hydrograph in the reference situation. In the same way, we find no aggravation ranges for q_{peak} while other researchers did, for other catchments (see *Background*).

In terms of preserving receiving waters (i.e. the two last indicators), volume provisions perform well even for small constraint values. As expected, this form of provision seems much more effective, toward this objective, than the other. With regard to avoiding sewer overflows (i.e. the first indicator) the results are more surprising: the same values that can be obtained through runoff rate provisions are accessible through runoff volume provisions.

CONCLUSIONS

In this research, we developed a model of a real catchment in the Paris region in order to compare several levels of constraint for both runoff rate and runoff volume provisions. We considered two objectives: to avoid sewer overflows and to preserve receiving waters. To measure the performance of each provision we adopted three indicators: peak flow-rate for a reference design storm for the first objective; flow frequency and volume bypassing the treatment unit during a 23-month simulation for the second one.

The results show that runoff volume provisions are more effective than runoff rate ones for receiving waters preservation. For sewer overflows, both can reach the same performances. Thus, is it possible to replace all runoff rate provisions with more environmental-friendly runoff volume provisions? In theory yes, but two observations are needed:

1. While runoff rate provisions can be realized almost everywhere, infiltration is not always possible. Even if other possibilities to deplete stormwater exist (e.g. rainwater harvesting and reuse) they do not seem, today, capable to reduce runoff volume systematically over an entire catchment. In some catchment, thus, volume provisions are not applicable.
2. We did not consider, in our research, any form of implementation cost. Then, even if we find an equivalence of runoff rate and runoff volume provisions in terms of peak flow rate reduction, it is possible that, in terms of costs, this equivalence is not valid.

A promising solution, that deserves further research, is an integration of both runoff volume and rate provisions. It seems possible that this approach could gather the global advantages of both, involving smaller local costs.

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